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THESIS

PULSATING COMBUSTION DEVICE MINIATURIZATION

by

Robert Kenneth Crowe

December 1976

Thesis Advisor: M. F. Platzer

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PULSATING COMBUSTION DEVICE MINIATURIZATION

by

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL

December 1976

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Chairman, Department of Aeronautics

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ABSTRACT

The phenomenon of pulsating combustion remains one of the least understood forms of combustion. In this thesis, combustion oscillations are classified into the categories of chamber oscillations, system oscillations, and intrinsic oscillations. Two pulsating devices, the pulsejet and the Reynst combustion pot, were studied in some detail. Experimentation was conducted to determine the miniaturization capabilities of the devices. Conclusions were drawn concerning the practicality of size reduction, and applications of the devices were suggested. Areas of possible future research are delineated that would further the development of the devices and their miniaturization.

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LIST OF SYMBOLS

1. a.....speed of sound
2. A.....area
3. $c_{1,2}$..constants
4. c.....speed of sound
5. C_v....specific heat
6. f.....frequency
7. F.....thrust
8. g.....acceleration due to gravity
9. h.....depth
10. H.....heat added per hour
11. L.....heat of vaporization, length
12. m.....mass
13. p.....pressure
14. Q.....heat
15. R.....gas constant
16. S.....area
17. t.....time
18. u.....velocity
19. V.....volume

20. W.....air flow rate

21. γ.....specific heat ratio

22. δ.....diameter

23. ϵ.....amplitude

24. η.....efficiency

25. θ.....taper angle

26. ρ.....density

27. ω.....frequency

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I. INTRODUCTION

In recent years there has been increased interest in short take off and landing aircraft. One method of achieving increased lift is through boundary layer control. Boundary layer control is achieved by injecting an airflow at some point on the airfoil or by sucking air from the airfoil surface to acquire a higher speed air flow over the surface of the wing. It is conceivable that the boundary layer control device could use both sucking and injection in a cyclic manner to yield greater lift. In the past, suction or air injection was achieved from compressors through heavy and expensive ducting which were not always compatible with stringent aircraft requirements.

Ideally, the boundary layer control device must be controllable, reliable, small, simple, and of minimum weight for aircraft applications. One possible method of energizing the boundary layer is to move the energy conversion device to the wing instead of ducting the airflow to the wing. Such a method can use a pulsating combustion device.

Pulsating combustion, combustion oscillations and combustion instability are several names for a phenomenon of combustion which takes place under conditions of fluctuating pressure, velocity, temperature and heat release intensity. The phenomenon of pulsating combustion instability has been both a problem and a goal in propulsion efforts and applications. Pulsating combustion has been used successfully for propulsion, fogging, heat generation and many other useful applications. Pulsating combustion has

also been a source of problems in furnaces, boilers and rockets.

One element that stands out in a study of pulsating combustion devices is the simplicity of a device with few or no moving parts, yet reliable mathematical analysis has continued to elude researchers.

There are several distinct advantages of pulsating combustion devices[1];

a) simplicity of construction

b) use of constant-volume combustion yielding higher combustion intensity

c) heat transfer increased by velocity fluctuations

d) pressure generation in the chamber, enabling exhaust gases to be readily cleared

e) cost of materials.

There are also some inherent problems in pulsating combustion devices;

a) excessive noise

b) unreliable performance of mechanical valves

c) restricted self-resonant combustion turn-down ratios.

One objective of this thesis is to review and analyze the current literature of pulsating combustion devices as a mechanism for the conversion of petroleum energy to air flow energy. In support of this objective, combustion

instabilities can be classified according to frequency, causes and characteristics. Two devices, the Reynst pot and the pulsejet, were investigated with emphasis on size reduction.

Literature concerning the Reynst combustor, a low frequency combustor which operates with no moving parts while producing useful heat and air flow, is reviewed for historical development and theoretical modeling. Results of past research are analyzed for geometrical effects of the chamber on the phenomenon, as well as fuel requirements. Past construction techniques are investigated. Experiments which were conducted to confirm geometrical effects and to develop a significant size reduction of the Reynst combustor are presented.

Literature for the pulsejet, a combustor of acoustic frequency with very few moving parts and an excellent thrust-to-weight ratio, is examined for historical and theoretical development. Construction characteristics are similarly reviewed. A brief summary of Lockwood's research in miniaturization of a pulsejet is presented. Experimental work, conducted to shorten an existing small pulsejet and to determine the effects of configuration change on the thrust characteristics is presented.

Finally, literature and experimental results are summarized and the directions of future pulsating combustion research are suggested for pulsating combustion devices.

II. CLASSIFICATION

Combustion oscillations occur in a wide variety of combustion devices such as rockets, turbines, pulsejets, and boilers. These oscillations appear in quite different forms, of which some are desirable and the rest highly undesirable. Three distinct headings can be used to classify combustion oscillations [2]: system oscillations, combustion chamber oscillations, and intrinsic instabilities.

A. SYSTEM OSCILLATION

Examples of system oscillations were among the earliest oscillations mentioned in the literature. The interaction of two processes, one occurring in the combustion chamber and the other occurring in at least one other component of the device, is used as the criterion for classification as system oscillation. The interaction of the processes results in a feedback of energy to the combustion chamber. Thring [3] points out in "Combustion Oscillation In Industrial Combustion Chambers", that even one part in 10^4 of the combustion energy fed back into oscillations is sufficient to overcome the natural damping of the combustion chamber pressure fluctuations. System instabilities possess the lowest frequencies of combustion oscillations, ranging from one or two hertz, up to acoustic frequencies of two to three hundred hertz. Amplitudes can reach as much as fifty percent of chamber pressure.

In previous years, system oscillations in industrial furnaces and boilers received most of the attention in this heading. The gas-exhaust duct provided the feedback mechanism for what is now known as Helmholtz resonance with a frequency determined by the formula:

$$\omega = a\left(\frac{S}{hV}\right)^{1/2} \qquad (1)$$

In this formula, ω is the frequency, a is the speed of sound, V is the volume of the furnace; S is the area of the duct and h is the duct length.

A time lag between injection and propellant combustion provides a system feedback in liquid rocket motors that causes an instability known as "chugging". The "singing-flame" observed by Byron Higgins [4] in 1777 is an example of feedback from the fuel line to maintain oscillations. The Reynst pot is a particularly interesting example of system oscillations which will be considered in detail later in this thesis.

B. COMBUSTION CHAMBER OSCILLATION

Combustion chamber oscillations are unsteady phenomena that occur within the combustion chamber and may be subdivided into three categories; acoustic, shock, and fluid dynamic. When the amount of energy going into an acoustic mode of a chamber exceeds the amount of energy extracted from that mode, an acoustic instability results. Combustion in chambers of rapid area change can excite the longitudinal mode corresponding to an antinode of a system of standing waves. The longitudinal mode is the most common in industry. A rarely observed phenomenon is the radial mode

since the driving mechanism requires the maximum heat release to occur on the chamber axis. The increased use of solid fuel which has rapid heat release close to the walls of a cylindrical chamber provides the excess energy to cause tangential mode instability.

If the combustion intensity is high, a shock instability of combustion chamber oscillation can develop. These instabilities can propagate at or above sonic velocity, and in some cases may have their origins in acoustic oscillations (longitudinal, tangential, or spiral) that have grown into steep-fronted pressure waves. The shock wave is driven by a combustion zone close behind the wave which can only occur with a proper propellant distribution.

Fluid-dynamic oscillations are characterized by the formation of vortices in the combustion chamber. The theoretical description of this instability is virtually nonexistent due to the complicated nonlinear flow involved. With the exception of the fluid-dynamic oscillation which has a low frequency of the order of twenty hertz, the combustion chamber oscillations are of acoustic frequency or higher. For the case of longitudianl mode with supersonic exhaust the frequency corresponds to a pipe closed at both ends, whereas with subsonic exhaust the frequency corresponds to a pipe closed at one end and open at the other. The amplitudes of chamber oscillations can vary from a few per cent of ambient to amplitudes capable of disintegration of the chamber. The laboratory tunnel burner and the pulsejet are two of the most common devices making use of combustion chamber oscillations. The pulsejet will be covered to a greater extent in a different portion of this thesis.

C. INTRINSIC OSCILLATIONS

The final heading of combustion oscillations is that of intrinsic instability. These oscillations are attributable to the reactants and are not a function of external influences. They are of particular concern in solid fuel propellants. An example of this type of instability would be the periodic shedding of aluminum from the surface of a burning propellant (This is subject to chamber influences such as pressure and axial velocity.)

D. OSCILLATION CHARACTERISTICS

Division of combustion oscillation into headings is somewhat arbitrary, especially in the region of acoustic periodicity. However, a few generalities can be drawn from Putnam [4] which are useful in understanding, applying, or suppressing pulsating phenomena.

According to Putnam [4] there are several ways of causing oscillations in a gas medium by the addition of energy.

a) Pulsation in the supply rate may provide the necessary energy required to cause combustion oscillations

b) Pulsations in flame front area can provide a periodic heat release (These may be flow past flameholders and natural vortex shedding.)

c) Pressure usually increases as the heat release rate

increases and is usually in phase (This is a common problem in high pressure combustion systems.)

d) Periodic variation of the pressure or velocity can cause periodicity of fuel breakup or fuel injection (This variation can result in a periodic combustion rate feeding the oscillation.)

e) Periodic composition changes can also feed the oscillations.

III. REYNST COMBUSTOR

A. HISTORY

One of the most interesting of the system oscillations is the Reynst pot phenomenon. The discovery of this phenomenon was the result of an accident. F. H. Reynst dropped a burning match into a near empty can of alcohol. Instead of simply burning or going out, the can of alcohol began to rumble at a low frequency. From this beginning, pulsating combustion became the vocation and avocation to which Reynst devoted his life.

In the collection of Reynst's works [5] edited by M. W. Thring, Reynst describes an experiment with a jam jar with a lid which had a hole pierced in it. The jar had an internal diameter of about 70 mm and an opening of 13 mm diameter in the lid. The jar was filled to a depth of 5 mm with methylated spirits and then shaken. A lighted match was brought to the hole in the lid and the mixture exploded. This explosion was followed by a series of explosions reaching a maximum frequency of 20 explosions per second. Scavenging, ignition, and combustion were controlled automatically without mechanical valves or any other moving parts.

The early development of this form of pulsating phenomenon can be traced in the patents and papers of Reynst [5]. In 1933 Reynst documented his discovery by a notarized deed in which he describes an apparatus to generate energy

of air in motion. A procedure and device for the generation and transfer of heat was patented in 1938 as the first practical application of the discovery that originated in an alcohol can. Water cooling was added to make the operation of cyclic explosions continuous and to provide one means of using the heat generated from the combustor. A further improvement was the addition of a vortex ring which was a water cooled, truncated cone-shaped device. The purpose of this ring was to strengthen the vortex at the bottom of the chamber. The introduction of fuel in atomized form was a significant modification over the previous device both in form (atomized vice liquid) and in location (throat vice bottom) of introduction. The resulting device proved controllable from 2 to 100 cycles per second and possessed a high heat transfer coefficient.

An early addition to the combustion pot was an exhaust pipe to carry the products of combustion into the open. The pipe had sharp edges with a diameter equal to the diameter of the orifice of the pot. Placing the pipe a short distance from the orifice allowed the exhaust gases to flow into the pipe without drawing the fuel air mixture with them. The addition of the pipe also allowed a larger diameter orifice to be used as well as a larger pipe which resulted in higher frequencies. A chance failure in a portion of the flue of the combustion pot caused a sudden opening of the fuel regulator. This opening resulted in the combustion pot increasing frequency and achieving resonance with the natural frequency of the air column. Even greater pressure amplitudes were observed with the pot in resonance. The device which measured one meter from chamber bottom to diffuser outlet, had a natural frequency of 200 cycles per second. The measured pressure amplitude was between +0.7 and -0.5 atmospheres with a fuel flow of 4 kg per hour and a combustion intensity of $40X10^6$ kcal/m^3/hr.

Reynst made use of a piston for the bottom of the combustion pot and a specific starting procedure to regularly achieve resonance and the performance associated with resonance (fig. 1). When gasoline injected into the chamber was ignited by a spark with the piston fully withdrawn, a pulsation of approximately 10 Hz occured. Once warmed gasoline and intake air were well mixed and the injector valve was closed, the frequency increased to 50 Hz. By quickly narrowing the gap between diffuser and chamber, and simultaneously turning the gasoline full on, the explosions were brought into resonance with the natural frequency. The piston was moved up to reduce the volume of the chamber.

Reynst thus developed and patented an effective pulsating heating device that yielded an impressive combustion intensity. It should be mentioned that the noise generated by this device could be heard for a distance of six miles. Little was done to further develop the combustion pot beyond the work of Reynst. This lack of development seemed to be the result of a lack of qualitative and quantitive theoretical understanding of the processes involved.

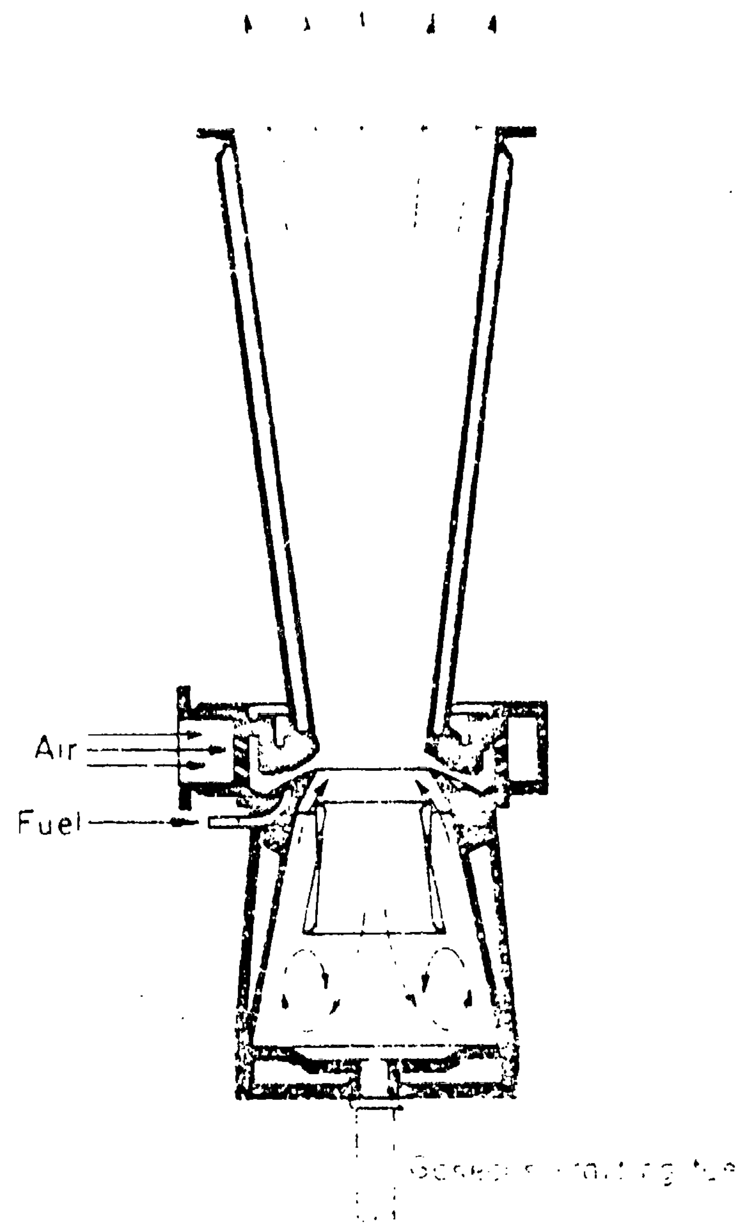

Figure 1 - REYNST COMBUSTOR [5]

B. MATHEMATICAL MODEL

The early work of Reynst attracted the attention of J.W. Porter who began a study of this unusual form of combustion. The cycle as described and studied by Porter [6] began with the constant volume burning of an alcohol-air mixture in a closed cylinder with a small hole in one end. The pressure increased above atmospheric as a result of this burning. The burned gases flowed out through the orifice decreasing the pressure of the vessel. The cooling of the vessel caused the cylinder pressure to drop below atmospheric causing a jet of cool fresh air to enter the chamber which in turn mixed with the alcohol. Residual burning gases then ignited the alcohol/air mixture and repeated the cycle.

There are two methods of combustion in a container with a single orifice. One method is constant pressure diffusion burning which has relatively gentle laminar or turbulent diffusion flames. The second method is pulsating combustion which results in low frequency (less than 100 Hz) pressure and flow oscillations. Chamber construction and orifice diameter determine which of the methods of combustion occur.

A major achievement of Porter's study was his theoretical analysis and modeling of the Reynst phenomenon. In Porter's work, a number of assumptions were made in an analysis of the pressure "blow down" after an explosion. Chemical reaction rates were assumed to be negligible due to explosive burning of most of the reactants in the chamber. While assuming a zero reaction rate ignores the residual burning gases that ignite the following cycle, the assumption was reasonable for the limited scope of the model. Uniform conditions were assumed throughout as a

result of a small chamber size and low frequency of combustion oscillations as compared with the natural acoustic frequency of the container. The acceptance of uniform conditions would have to be reviewed for pulsating phenomena near reasonance. For the temperatures and pressures involved, the perfect gas was a valid expedient assumption.

Having made these assumptions, the conservation equations were written. The continuity equation became:

$$\frac{d\rho}{dt} = \frac{(\dot{m}_f - \dot{m}_e)}{V} \qquad (2)$$

where $\dot{m}_f$ is the fuel vaporization rate, $\dot{m}_e$ is the mass flow rate through the opening and V is the volume of the chamber.

The energy equation was expressed as;

$$\frac{dp}{dt} - \left(\frac{\gamma p}{\rho}\right)\left(\frac{d\rho}{dt}\right) = -(\gamma - 1)\frac{(\dot{m}_f L + \dot{Q})}{V} \qquad (3)$$

where L is the heat of vaporization of the fuel, p is the pressure, γ is the specific heat ratio, and $\dot{Q}$ is the total heat loss through the walls of the chamber.

With the density and pressure variation assumed to be small:

$$\left|\frac{(\rho - \bar{\rho})}{\bar{\rho}}\right| << 1 \qquad (4)$$

and

$$\left|\frac{(p - p_a)}{p_a}\right| << 1 \qquad (5)$$

the mass exhaust rate $\dot{m}_e$ was expressed as

$$\dot{m}_e \simeq \begin{cases} A\left(\frac{2\bar{\rho}}{\rho_a}\right)\left[\rho_a(p-p_a)\right]^{\frac{1}{2}} & \text{discharge} \\ A(2)^{\frac{1}{2}}\left[\rho_a(p_a-p)\right] & \text{suction} \end{cases} \qquad (6)$$

In this analysis the non-steady acceleration term in the momentum equation was neglected and modified orifice diameters were included. $\bar{\rho}$ is the average density, A is the area of the orifice, and ρ_a and p_a are the ambient density and pressure respectively. Porter integrated the momentum equation across the orifice and obtained:

$$\rho_a u_e^2 = (p-p_a) + \left(\frac{1}{\omega_H}\right)^2 \frac{d^2 p}{dt^2} \qquad (7)$$

where the Helmholtz frequency ω_H is

$$\omega_H = \alpha\left[\frac{3\pi^2}{32}\left(\frac{\delta}{V}\right)\right] \qquad (8)$$

and the exhaust velocity u_e is

$$u_e = -\left(\frac{V}{\gamma p_a A}\right)\left(\frac{dp}{dt}\right) \qquad (9)$$

The orifice diameter is δ . In the derivation of (7), an effective mass of air of

$$\left(\frac{32}{3\pi^2}\right)\left(\frac{\rho_a A^2}{\delta}\right)$$

was used as obtained from Rayleigh in <u>The Theory of Sound</u> [7].

At this point the fuel vaporization rate $\dot{m}_f$ and the wall

heat transfer rate were assumed to be constant. Equations (3), (6), and (7) were combined and integrated to yield:

$$(y_{1max} - y_1) - \log\left[\frac{(1 + y_{1max})}{(1 + y_1)}\right] = \bar{t}_1 \qquad (10)$$

$$\text{for } 0 \leq t \leq t_0$$

and

$$\log\left[\frac{1}{(1 - y_2)}\right] - y_2 = \bar{\bar{t}}_2 \qquad (11)$$

$$\text{for } t_0 \leq t \leq \tau$$

where

$$y_{1,2} \equiv \left\{\frac{A_{1,2}(p_a \rho_a)^{\frac{1}{2}}}{(\gamma-1)\left(\frac{\rho_a}{\gamma p_a}\right)(\dot{m}_f L + \dot{Q}) - \dot{m}_f}\right\} * \left[\frac{|p - p_a|}{p_a}\right]^{\frac{1}{2}} \qquad (12)$$

and

$$t_{1,2} = \left\{\frac{\gamma (A_{1,2})^2 p_a}{2V\left[(\gamma-1)\left(\frac{\rho_a}{\gamma p_a}\right) * (\dot{m}_f L + \dot{Q}) - \dot{m}_f\right]}\right\} * t \qquad (13)$$

and

$$A_1 = A\left(\frac{2\bar{\rho}}{\bar{\rho}_a}\right)^{1/2} \qquad A_2 = A(2)^{1/2}$$

and $y_{1,max}$ is y_1 when pressure p is equal to p_{max}. The time for transition from discharge to suction was obtained by letting $y_1 = 0.0$.

$$(\bar{t}_1)_0 = y_{1max} - \log(1 + y_{1,max}) \qquad (14)$$

τ represents the beginning of rapid combustion and transition from suction to discharge. This theoretical development did not predict the time to rapid combustion nor the maximum pressure of the phenomenon since chemical reaction rates were ignored and only a portion of the cycle was considered. The waveform of the discharge and beginning suction, however, is predicted by this model.

C. RESULTS OF PORTER [6]

Porter's experimental investigation centered in three areas: (1) measurements for a 3.64 in internal diameter pipe; (2) high speed schlieren motion pictures of a box with pyrex sides; and (3) miscellaneous experiments. A combustion chamber was made from a 3.64 in. internal diameter water cooled iron pipe with a plate containing a sharp-edged circular orifice covering the top. A piston which formed the bottom allowed the chamber length to be varied from 5 to 12 inches. Combustion was initiated using a spark plug ignition system. Pressure amplitude measurements were taken as a function of time. A constant cooling water inlet temperature and flow rate were maintained and outlet temperatures were measured to determine the heat transfer rate. Fuel consumption was determined by micrometer measurement of fuel depth and an electronic stopwatch. The main objective of this area of investigation was to determine the relations among frequency, pressure amplitude, burning rate and chamber geometry.

A second area of investigation attempted to obtain qualitative information on flow patterns, mixing and

ignition. The device used in this area was a $3^7/_8$ in X $3^7/_8$ in chamber with a metal frame and pyrex walls. After the pulsation occurred for about 15 seconds, the condensed water on the glass walls evaporated and high speed photographs were made. Miscellaneous experiments were made to determine what fuels could be used, effects of oxygen concentration, orifice shapes and location, multiple orifices and chamber diameter and shape. This area provided general empirical information on the phenomenon.

When the measured values of maximum pressure, fuel burning rate, and wall heat transfer rate were used in the equations previously derived, a substantial agreement with theory was noted which indicated wall heat transfer and fuel vaporization were the driving mechanisms which brought the chamber below ambient pressure. The Helmholtz frequency of 153 Hz was substantially higher than the 50 Hz average frequency ω for the device which demonstrated the assumption of

$$\left(\frac{\omega}{\omega_H}\right)^2 \ll 1$$

was correct.

The high speed Schlieren photographs of Porter revealed a great deal concerning the fluid dynamics. When air was drawn into the combustion chamber, a vortex was formed near the top with a turbulent air region at the bottom. Rapid combustion was observed to begin shortly after the inflow jet reached the surface of the liquid fuel.

Empirical relations between geometry and phenomenon characteristics were noted by Porter. An inverse linear relation was observed between frequency f and chamber length h:

$$f \propto \frac{1}{h} \qquad (15)$$

A complex relation was observed in the frequency dependence on orifice diameter. Two portions of the cycle, blow down to suction and mixing, can be shown to be dependent according to theory on orifice diameter. It was shown that frequency for the cycle could be expressed as

$$f \simeq \left[h\left(\left(\frac{c_1}{\delta^2}\right) + c_2\delta^2\right)\right]^{-1} \qquad (16)$$

where c_1 and c_2 are constants and δ is the orifice diameter.

Experimental evidence indicates that frequency increases as orifice diameter increases, under blow down time domination, and that frequency decreases with increasing orifice diameter once mixing/ignition time dominates the cycle. The highest frequencies for the 3.64-in combustor occurred with an orifice diameter of $^{20}/_{32}$ inches for all chamber lengths. Pressure amplitudes in all cases were approximately one tenth ambient pressure.

Chamber geometry more than any other factor determined whether the combustion was of a diffusion or an oscillatory nature. For the 3.64 in diameter chamber the regions of regular sustained oscillations occurred at depths from 7.5 to 11.0 in. and an orifice diameter from $^{9}/_{16}$ in. to $^{11}/_{16}$ in. with maximum stability occurring at a depth of 9 in. and an orifice diameter of $^{21}/_{32}$ in. The most stable

orifice diameter to combustion chamber length ratio was therefore approximately 0.18. This compared closely to the 0.2 ratio mentioned by Reynst [5] in his jam jar experiment. A length to diameter ratio was computed to be 2.5 for the most stable operation of Porter's device. Maximum frequency occurred at an orifice to chamber diameter ratio of 0.17; maximum pressure amplitude, at a ratio of 0.14; and maximum fuel burning rate at a ratio of 0.15.

Other experiments showed the chamber worked well with kerosene or gasoline. A 2.5 in diameter chamber was the smallest device reported.

Conclusions of the study by Porter were that the Reynst phenomenon yielded burning rates that were as high as eight times the steady diffusion burning rate. For constant diameter combustion chambers, it was determined that pulsation was only possible within certain chamber length and orifice diameter ratio limits.

D. CONSTRUCTION

The construction of the devices of Reynst [5] and Porter [6] as well as the device described by Beale, Clarke, and Everson [8] had many similarities. In each design, the mechanism for heat transfer from the combustion chamber was fundamental. The walls (iron for Porter's device) had a critical effect on heat transfer. Light guage brass sheet was used by Beale, et al. for strength, accessibility and thermal conductivity. With the small pressure variation, strength of material was not necessarily a dominant factor in the construction of the devices. Location of the spark plug was selected by trial and error in each case.

E. EXPERIMENTAL RESULTS

Experimental work for this thesis began by attempting to duplicate the jam jar experiment of Reynst (fig. 2). A glass jar with a mouth diameter of 2.4 in. and a height of 4.84 in. was used for this portion of the study. After an orifice of 0.45 in. diameter was made in the center of the metal lid, a sealant was applied to the rim and lid to ensure an airtight seal. The jar was filled with denatured alcohol to a depth of 1/4 in. After the orifice was covered, the jar was shaken vigorously to attain a good fuel and air mixture. Excess alcohol was wiped away from the orifice and air was then blown into the jar. A burning match brought near the orifice caused the mixture to explode and initiate pulsating combustion.

Frequency measurement was completed by a microphone fed into a real-time analyzer. Measurements indicated a dominant though somewhat irregular frequency of 45 to 50 cycles per second with higher frequencies present. All experiments were kept under 10 seconds except one to preclude breakage of the jar. To determine the method of failure, one jar was allowed to run until breakage occurred. Heat generated from combustion resulted in cracks occurring completely around the bottom of the jar causing the jar to cease pulsation. It should be noted that failure of the jar was not hazardous in any way to the experimenter due to the low pressure variations involved.

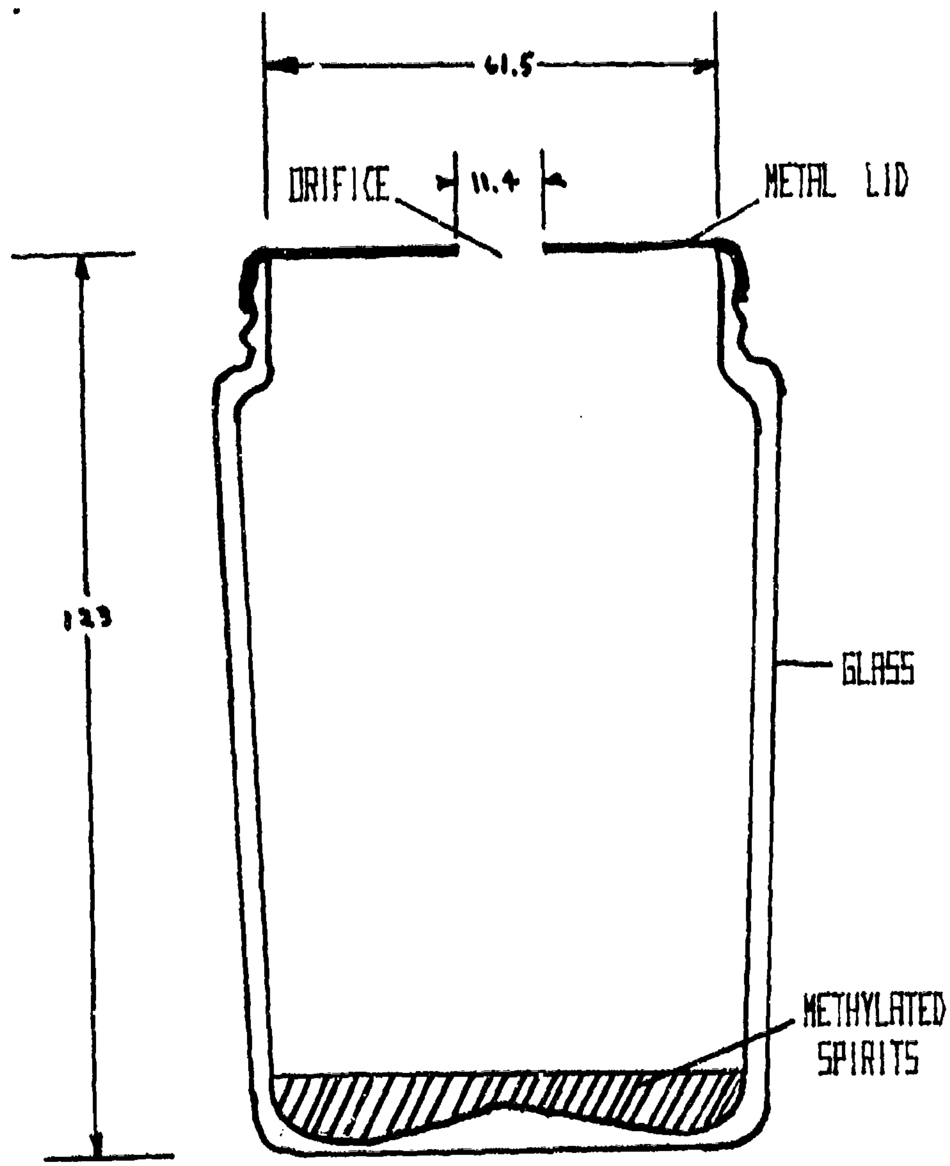

Figure 2 - GLASS (JELLY JAR) COMBUSTOR

In order to overcome the breakage problem and to reduce the size of the pulsating device, a box shaped device was constructed. Possible chamber dimensions were 2.25 X 3.025, 2.25 X 2.325, and 2.25 X 1.625 inches with a variable depth to 4.25 in. One side of the box was tempered safety glass with the remaining sides constructed of steel. Sealant was necessary to maintain the pressure integrity of the device. Thin brass strips were used to modify the orifice to determine an operative (square) orifice area. Starting procedures were similar to those used for the jam jar experiment (fig. 3).

The box device demonstrated that area ratios were more important than the exact shape of the chamber and orifice. Area ratios of 0.04 (which corresponds to diameter ratios of 0.2) were most successful. The requirement for a depth to chamber ratio corresponding to that used by Porter for maximum stability was also confirmed. While the objective for a smaller pulsating combustion device was achieved with the chamber measuring 2.25 X 1.625 in, the operation was not continuous beyond 20 seconds.

The major problem with the box device was the heat transfer characteristics of the chamber. Even when the device was submerged in water, cooling was not sufficient to maintain oscillations. The specific cause of the lack of sufficient heat transfer was attributed to the type of material (steel and glass) and to the thickness (1/4 in).

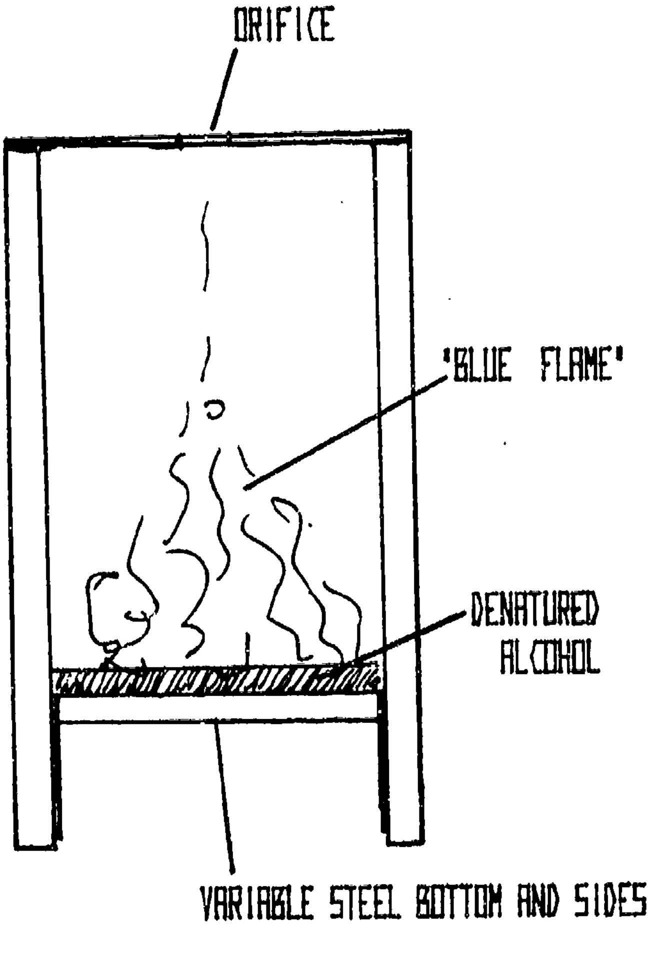

Figure 3 - BOX-SHAPED COMBUSTOR

To improve the thermal conductivity of the chamber and to further the exploration of still smaller chambers, the next series of devices was constructed from copper tubing of varying smaller diameters. The copper tubes were closed at one end and fitted at the other end with a threaded brass ring (fig. 4). A brass cap ring was made for each tube which would accept a light gauge brass disc in which the orifice had been cut. Orifice diameters were changed by changing discs. Tubing internal diameters were 1.25, 1.0, and 0.75 inches. A small brass tube was soldered to the base of each of the 4 inch long combustors to provide a method of adding additional fuel to the combustor when it was operating. A 2.5 in. cooler jacket was constructed to allow water cooling of the combustors (fig. 5). While the method of starting was similar to that of the previous devices, the addition of the small brass tube allowed air to be bubbled through the denatured alcohol to assimilate the desired fuel and air mixture. Depth adjustments were achieved by adding alcohol to the desired depth.

While it was hoped that the decrease in volume and the relative increase in the surface area would allow the combustors to function without water cooling, this turned out not to provide enough heat transfer. A vigorous flow of water was required to achieve continous oscillatory operation of the 1.25 in and the 1.0 in combustors.

Orifice diameter to combustor diameter ratios required a significant increase for stable operation over the stable ratios for larger devices. The 1.25 in combustor had an orifice diameter of 0.295 in for a ratio of 0.235. The 1.0 inch combustor had an orifice diameter of 0.24 inches for a ratio of 0.24. Oscillation for the 0.75 in. combustor was not achieved. Chamber depths were approximately 3 in. and 2.5 in. for the 1.25 in. and the 1.0 in. combustors,

respectively. As fuel burned down and the chambers effectively got deeper, an audible decrease in frequency could be discerned followed by erratic operation which was corrected by adding fuel. The extreme requirements for heat transfer rendered operation without water cooling unfeasible. If wall thickness were significantly reduced (which would be possible since the pressure variations are low) an increase of heat transfer by a factor of two to four might have been realized. Cooling fins could have added an additional 50 per cent to the cooling rate (at an increase in size). However, to achieve operation in free air as opposed to flowing water would have required an increase in heat transfer by a factor of twenty.

While the objective of size reduction in a pulsating combustion device was met by the copper combustors which demonstrated that low frequency combustors could be constructed with an internal diameter of one inch and a length requirement of only 2 1/2 inches, the problems of heat transfer and low pressure differentials overshadowed the aircraft application potential.

As a result of problems encountered, this study shifted to experimentation and modification of an existing commercially available miniature pulsejet to achieve a smaller pulsating combustion package.

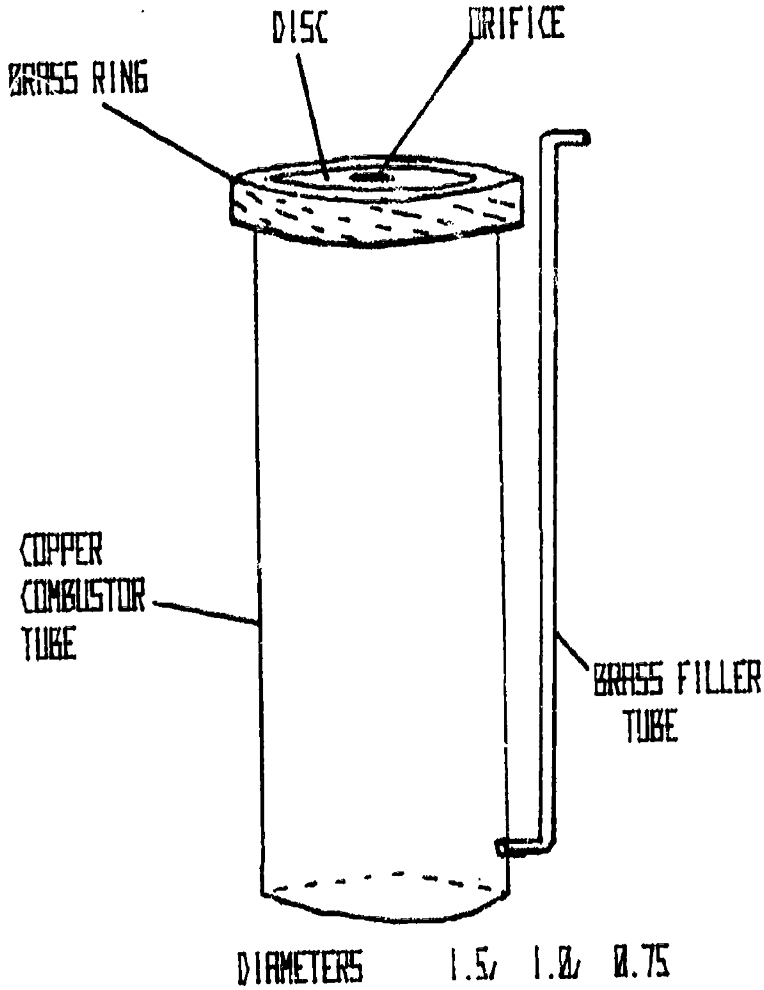

Figure 4 - COPPER TUBE COMBUSTORS

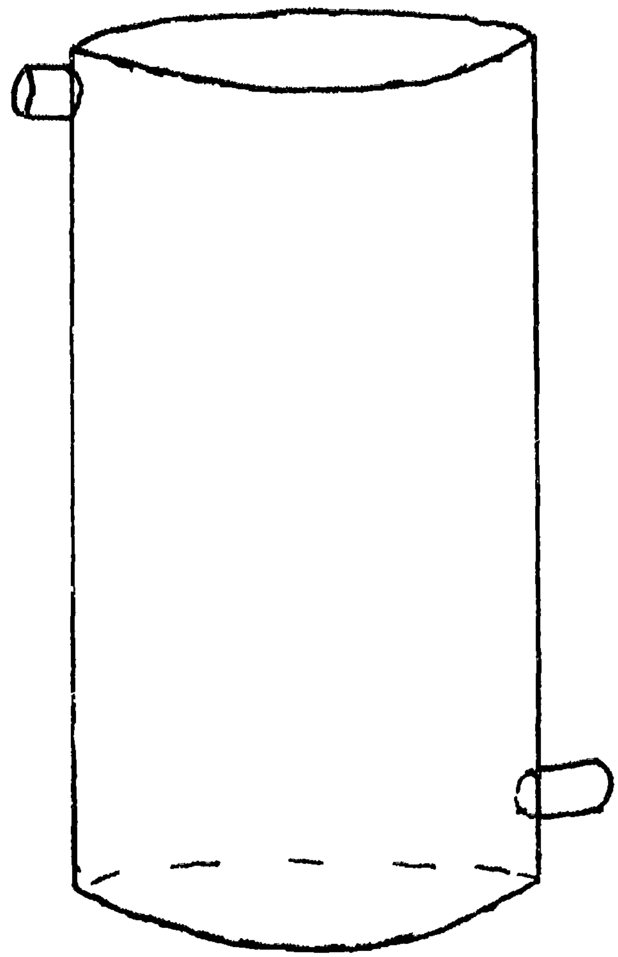

Figure 5 - WATER COOLER FOR COPPER TUBE COMBUSTORS

IV. PULSEJET

A. HISTORY

The most famous device using combustion chamber oscillations is the pulse jet. Near the beginning of the century, Esnault-Pelterie attracted the attention of many inventors in a search for a "pistonless musical frequency engine" to power aircraft.One of those attracted was Marconnet, who proposed a valveless pulsating combustion engine in 1909. Marconnet's work was theoretical, and apparently there was never even a laboratory model constructed. Due to lack of practical applications and conservative engineering thinking, Marconnet's work was ignored and forgotten until Schmidt attempted to patent a similar device in 1930.

In the area of pulsejets, Schmidt "planted the seeds and tended the field" but it was Diedrich who "reaped the harvest and brought it to market" in the form of the infamous V-1 Buzz Bomb [5]. The Schmidt tube attempted to use mechanical valves and shock wave phenomena to maintain oscillations. Application of a cylindrical and later conical tube without bulges offered the best conditions for wave propagations. Schmidt's success with the demonstration of the feasibility made possible the "active service" application of the Schmidt tube or the propulsive duct as it is sometimes known. The "active service" application was Diedrich's Argus engine which was incorporated into the V-1.

Following the second World War, research was carried on in France and in the United States. These studies generally concluded that the pulsejet was inferior to other methods of propulsion. Project Squid was the United States Navy's effort in pulsejet research, while in France SNECMA became the center of research. Russia maintained interest in the Schmidt tube and reportedly built V-1 type flying bombs, capable of carrying four metric tons at 1200 kilometers per hour.

While much was learned from the investigations following the war, many unknowns continued to cloud the development of the pulsejet. Applications were generally specific, such as sail plane propulsion, fogging and snow clearance. If a single cause could have been affixed to the frustration of expectations for the Schmidt tube, it would have been the lack of theoretical development to support experimental work.

B. MATHEMATICAL MODEL

One general theoretical model for the propulsive duct was published by C. S. Tharratt [9] who began his analysis by using the Lenoir Cycle to describe the quasi-constant volume thermodynamic process. By assuming a perfect gas, the efficiency η of the ideal cycle can be expressed by the overall pressure ratio

$$\eta = 1 - \gamma\left(\left[\left(\frac{p_1}{p_0}\right)^{\frac{1}{\gamma}} - 1\right] \Big/ \left[\left(\frac{p_1}{p_0}\right) - 1\right]\right) \qquad (17)$$

where p_1 and p_0 are maximum and ambient pressures and

γ is the specific heat ratio. Thrust was derived by Tharratt by the following formula:

$$F = \left[\frac{p_0}{2(\gamma-1)}\right]\left\{\frac{\left[\left(\frac{p_1}{p_0}\right)^{\frac{\gamma-1}{\gamma}}-1\right]^{1}}{\left[1-\left(\frac{p_0}{p_1}\right)^{\frac{1}{\gamma}}\right]^{-(\gamma-1)}}\right\} \tag{18}$$

where F is the thrust and γ is the specific heat ratio. The use of carefully chosen approximations allowed the development of general equations for the motion of a large amplitude pulse,

$$\frac{\varepsilon}{L} = 1-\left[1-\left(\frac{\varepsilon_0}{L}\right)\right]^{\sin(nx)\cos(nct)} \tag{19}$$

in which ε is the pulse amplitude, L is the length, x is distance, The mass of air displaced becomes:

$$m = \left(\frac{\rho L}{g}\right)\left\{\left[1-\left(\frac{\varepsilon_0}{L}\right)\right]^{-\sin(nL)_{\pi}} - \left[1-\left(\frac{\varepsilon_0}{L}\right)\right]^{\sin(nL)_{0}}\right\} \tag{20}$$

and a general expression for the pressure within the duct is given by

$$\frac{p}{p_0} = \left\{1-(nL)\cos(nx)\cos(nct)\left[1-\left(\frac{\varepsilon_0}{L}\right)\right]^{\sin(nx)\cos(nct)} * \log_e\left[1-\left(\frac{\varepsilon_0}{L}\right)\right]^{-1}\right\}^{\gamma} \tag{21}$$

where g is the acceleration due to gravity, t is time and c is the speed of sound. More theoretically exacting equations were derived from these by graphical integration, spherical wave approximation, and fuel assumptions. The equation for thrust, when integrated, showed the Lenoir cycle to be a most efficient description. The heat added

per hour (if a caloric value of 10,300 C.H.U. per pound were used) can be expressed as:

$$H = \frac{C_v\, p_o\, A\, L\; 3{,}600}{R\, t_{0.360}\; 10{,}300} \int_{\frac{x}{L}=0}^{\frac{x}{L}=1} \left[\left(\frac{p_1}{p_o}\right) - \left(\frac{p_2}{p_o}\right)\right] d\left(\frac{x}{L}\right) \quad \frac{\text{lb.}}{\text{hr.}} \qquad (22)$$

where H is the heat added per hour, C_v is the specific heat, R is the gas constant and A is the area. The air consumption per area can be expressed as :

$$\frac{W}{A_1} = \left\{\left[\frac{2g\gamma}{(\gamma-1)}\right]\left(\frac{P_o}{V_o}\right)\left[\left(\frac{P_1}{P_o}\right)^{2/\gamma} - \left(\frac{P_1}{P_o}\right)^{\frac{\gamma+1}{\gamma}}\right]\right\}^{0.5} \quad \frac{\text{lb}}{\text{ft}^2\text{-sec}} \qquad (23)$$

where W is the air flow rate and A_1 is the cross sectional area.

Due to the difficulty of burning fuel at velocities greater than Mach 0.2, the ratio of inlet nozzle area to downstream duct area is extremely important. The area change of the duct provides a means to slow the flow of air. Tharratt's analysis predicted that the area ratio should be restricted to a range of 0.22 to 0.3 for reasonable thrust output with higher chamber output requiring the lower ratio. One engine would not run with an area ratio greater than 0.215.

The practical construction of a pulsejet can be divided into three areas: inlets, combustion chambers, and tail pipes. Of the three, the inlet valves were the single most critical in pulsejet construction. As a result of this criticality, a great deal of research has been completed on mechanical valves and to a lesser extent on aerodynamic valves.

C. CONSTRUCTION

Pulsejets have been sucessfully constructed using each of the two types of valves, mechanical and aerodynamic. The mechanical valve, typically, has been constructed of thin metal petals arranged near their seat to close and prevent backflow during the postive pressure of the chamber and to freely allow inflow of air into the chamber during the low portion of the pressure cycle. An important design consideration is to have the natural frequency of the valve near the frequency of the system and thus to require the minimum amount of force to open it. With the seat of the valve completely clamped half of the cycle, the gain of the transfer function of the valve was reduced to unity and the valve merely responded to forces. A certain amount of looseness was required for best operation to utilize the natural frequency response of the valve. Most research on mechanical valves has been directed toward longer life and increased reliability.

The aerodynamic valve overcame some of the limitations of the mechanical valve and could, through research, still be improved. One of the earliest pulsejet uses of aerodynamic or "fluidic" valves was in 1944 by Schubert and Dunbar [10] who built a pulsejet with several kilos of thrust. Due to performance limitations, nothing ever came of this design.

SNECMA's first efforts to achieve a fluidic valve were directed toward a "static" device which offered greater resistance to sustained flow in one direction than sustained flow in the opposite direction. A full understanding of the aerodynamic valve has not been achieved. Most of the

information was held in the form of patents on devices that have been found to work. The Telsa diode [11] was one of the early static devices which made use of reverse flow channels around tear-drop shaped obstacles. Many other fluidic valves made use of cups and vortex flows to achieve the fluidic diode effect. Most of the fluidic valves were based on the "static" performance which considered only the steady-state fluidic resistance for each flow direction. While this performance proved satisfactory though hardly efficient for pulsejets of initial investigation, SNECMA chose to direct further efforts toward the "dynamic" fluid diode which used phase shift of the wave reflecting from the free end of a cylindrical tube.

The results of these investigations by SNECMA resulted in the Escopette. Application to the glider "Emouchet" permitted the first unassisted take-off of an air breathing power plant with no moving parts in December of 1950.

In spite of the present low performance ratios, improvements seem certain to come about as fluidic logic theory advances. Similarities were noted by Marchal and Servanty [10] between fluidic flows and behavior of an electrical network. The four fundamental elements involved were 1) inertia which corresponded to self induction, 2) capacity effect which corresponded to capacitance, 3) a phase shift which was similar to the electrical cos w, and 4) a fluidic diode which corresponded to an electrical diode or rectifier.

In the words of Marchal and Servanty [10], "It would appear possible to imagine entirely static machines through which gaseous currents flow in the absence of any driving pressure supplied from an external source."

The second element of pulsejet construction was the

combustion chamber. Chamber size and tailpipe diameter largely determined the thrust of the devices according to the empirical relation of Tharratt:

$$\frac{V\,(\text{duct volume})}{L\,(\text{effective length})} = 0.00316\,F \quad (\text{thrust}) \qquad (24)$$

Lockwood found that a forty-five degree taper from combustion chamber to inlet significantly reduced failure by metal fatigue as compared to the previous inlet pipe joining at ninety degrees. The combustion chamber was the area of highest temperatures and required the maximum thickness of the pulsejet. A copper glow coil is characteristic of the Curtis Company pulsejet foggers (fig. 6). this copper coil adds stability of operation by maintaining a source of ignition temperatures.

Frequency was largely determined by the tail pipe as a result of the acoustic length of the duct. Frequency is equal to the velocity of sound, divided by acoustic length and divided by four. The tailpipe was subjected to temperatures just slightly below those of the combustion chamber. Increased performance was achieved by using slightly divergent tailpipes or bell mouths at the end of straight tube tailpipes.

In the years following the second World War, the pulsejet was studied as a major propulsion device and, as such, research was directed at making larger and more powerful pulsejets.

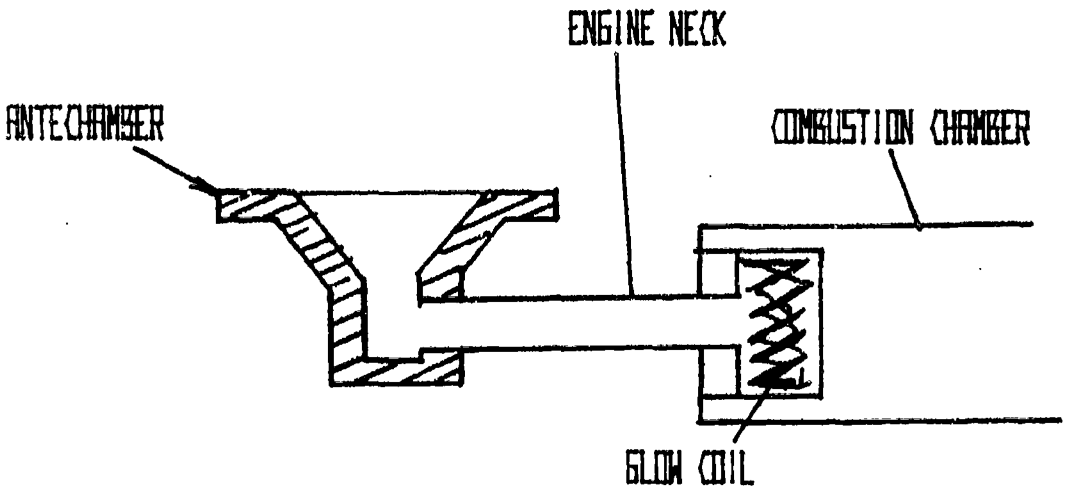

Figure 6 - INTAKE VENTURI AND COMBUSTION CHAMBER OF PULSEJET [12]

D. RESULTS OF LOCKWOOD [13]

Original work on miniaturization of pulsating combustion devices was begun in 1961 by the Hiller Aircraft Company, to determine feasibility of the pulsejet in VSTOL aircraft. The program began with efforts to scale down the 9.1" diameter valeveless pulsejet manufactured by the SNECMA Company into the 5 to 15 pound thrust range.

A number of problems arose as the pulsejets were reduced in size. As the combustor decreased in size, the resonant frequency increased with a corresponding decrease in the time for fuel air mixing. Fuel injection was a particular problem with the 4" diameter pulsejet.

Of the devices tested, the 5.25" combustor was selected to be the development engine. Attempts to decrease tail pipe length were initially frustrated by a corresponding decrease in performance. It was discovered that the length could be greatly shortened if the tailpipe was made divergent. However, as length decreased, the thrust to volume ratio decreased and the TSFC increased.The best thrust/volume ratio was achieved with the standard length (L/D 18.5) and the best TSFC was achieved with an L/D of 21 to 21.5.

A major breakthrough of the Hiller contract was the use of forty-five degree bulkheads at the inlet and exhaust of the combustor section. The forty-five degree modification allowed a reduced combustor length that resulted in an increase of thrust/volume ratio.

One of the most difficult problems encountered was that

of the fuel system. It was necessary to design the nozzles with size reduction as the primary design objective in order to reduce heat absorbed and therefore, vapor lock.

Lockwood found that commercially available nozzles were not small enough. Nozzle size and design, as well as location, required careful research. It was also necessary to create a flow restriction in order to prevent fuel blowback that would prevent fuel from returning to the nozzle before the next cycle.

The valveless miniature pulsejets tested by Lockwood showed difficulty in starting and unexpected blow outs at high fuel flow rates. A larger radius turn, more circular cross section, lengthened combustion chamber and tapered inlets were elements that assisted in the resolution of this problem.

In lengthening the combustion chamber there was a loss in thrust but this was offset by ease and reliability of starting. An inlet taper angle of $2\theta=1.5$ degrees allowed the L/D to be reduced to 16.4 by allowing reduction of length.

Lockwood demonstrated that many changes in configuration may be achieved with the pulsejet, providing that it retained its characteristic dimensions and component dimensional ratios (fig. 7).

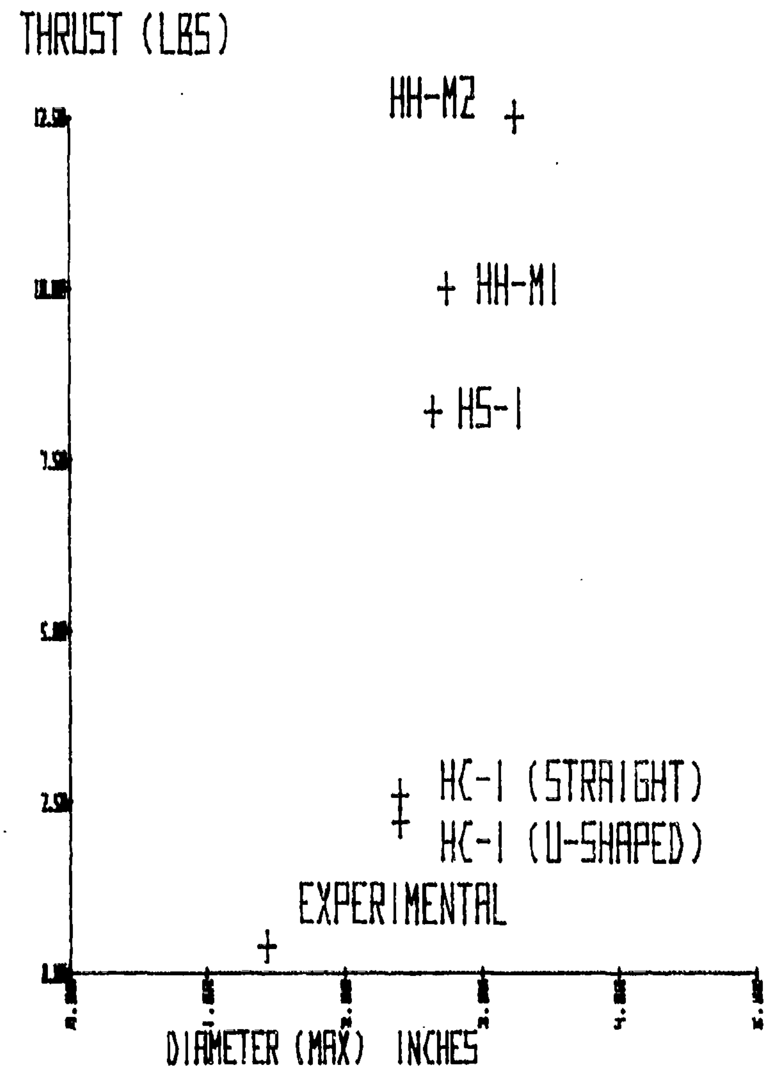

Figure 7 - THRUST VS CHAMBER DIAMETER OF THE PULSEJETS OF LOCKWOOD [13] AND OF THE PULSEJET INVESTIGATED.

E. EXPERIMENTAL RESULTS

A pulsejet from the Curtis Company was selected for miniaturization experiments in support of this thesis (fig. 8). The pulsejet was the central element of an insecticide fogger with an inlet to exhaust length of 44.375 inches. The effective length from the combustion chamber bulkhead to exhaust was 41.625 inches. Fuel input was achieved by a venturi effect leading through a mechanical valve to an inlet tube. The combustion chamber had a length of 7 inches with an internal diameter of 1.43 in. for 4 inches, tapering to 0.68 inch diameter in the remaining three inches. The tailpipe was straight tubing of 0.68 inch diameter without a bell mouth.

Operation of the pulsejet was on regular gasoline. Starting was accomplished by applying power to the spark plug in the inlet tube and pumping air through the venturi and venting a portion of the air to pressurize the fuel tank through a check valve.

The initial test was an attempt to verify that the package size of the pulsejet could be reduced by bending the device to a shorter overall length. This was accomplished by bending the tailpipe 180 degrees with a radius of 7.63 inches. Start and operation of the pulsejet was without any degradation of performance.

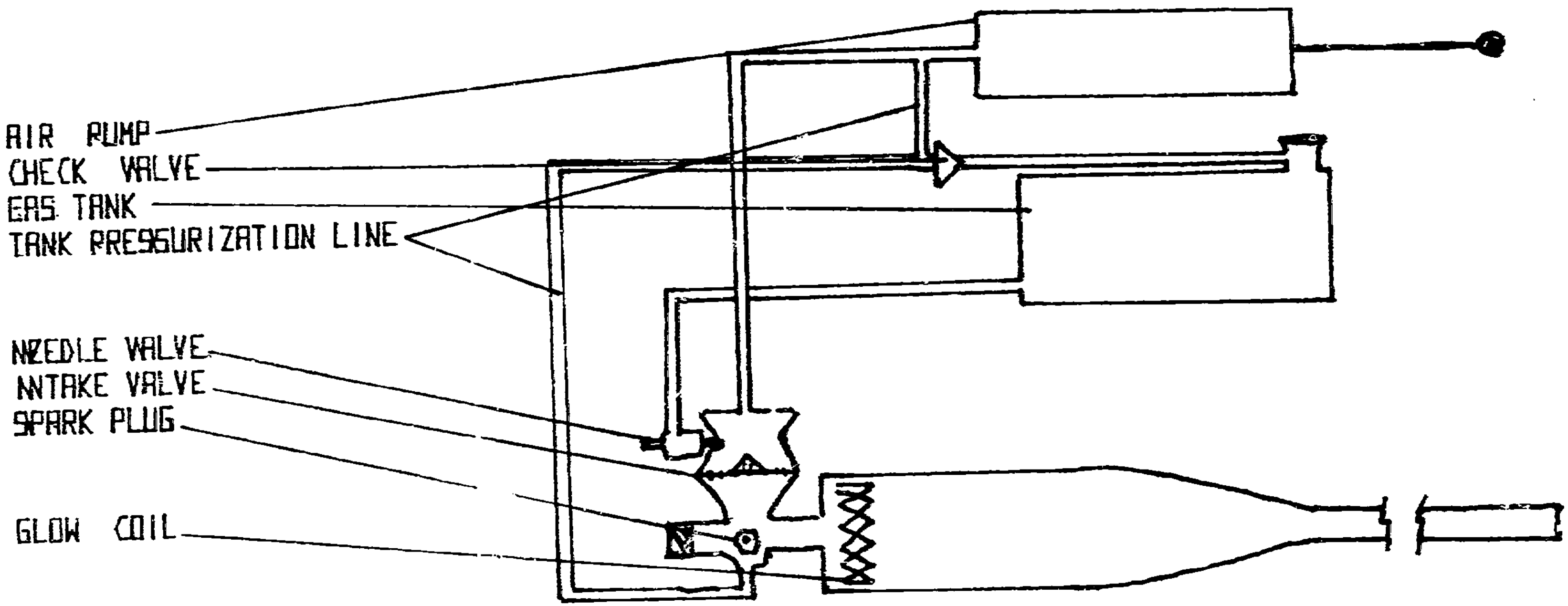

Figure 8 - DIAGRAM OF THE CURTIS "DYNA-FOG '70'" FOGGER PULSEJET

A brief attempt was made to replace the mechanical valves with an aerodynamic valve with greater static flow resistance in the outflow direction. The design of an aerodynamic valve alone for a device of this small size and this frequency of operation would have required greater expertise, time, and materials, than were available for this entire study.

The final direction for experimental study was an attempt to use a nozzle to "flatten out" the circular exhaust into a more useful sheet air flow and then to shorten the tailpipe to the limit of stable operation.

The test apparatus was assembled in a block house laboratory near the NPS supersonic wind tunnel. Temperature of the exhaust gases were measured by a chromelalumel thermocouple (type K) and read out digitally. Frequency measurements were made by recording the sound of the pulsejet for later analysis on an oscilloscope equipped with memory. The thermocouple was one quarter inch from the end of the exhaust nozzle though some measurements were taken of combustion chamber exterior and tailpipe exterior temperature. Thrust measurements were obtained from a thrust bed on which the device was mounted. Deformation of an aluminum ring on which were attached strain gages provided a means of obtaining a quantitative thrust measurement. Several weights were used to calibrate the thrust bed prior to each run. After each run, the millivoltmeter was rechecked for zero. The fuel tank was filled prior to each series of timed runs for every length. After each series, the quantity of fuel required to fill the tank was measured. Readings were taken by hand and later transferred to a minicomputer for data reduction.

When a mean operating temperature of 1000 degrees R was

used to compute the theoretical frequency, remarkably consistent results were achieved showing that frequency is dependent upon the length of the pulsejet (fig. 9). The theotetical frequency was computed by dividing the speed of sound by 4 and the length of the pulsejet and was represented by the symbol (X) in the figure 9.

Thrust of the pulsejet was affected by the addition of the nozzle and the decrease in length. The flattened nozzle addition caused a thrust decrease from 0.4 pounds to 0.35 pounds. As length decreased, there was a marked decrease in thrust from 0.35 pounds at 43-44 inches to 0.28 pounds at the limit of stable operation (fig. 10). Due to hysteresis of the aluminum ring of the thrust bed, the average thrust measurements are far more valuable than any specific measurement for a given length.

Fuel measurement was the most unreliable of the data taken. Inspite of the inaccuracies, a general decrease with length in the quantity of fuel used can be inferred but the rate of decrease is far less than the thrust rate of decrease. From the fuel and thrust measurements, it was determined that for the pulsejet of this size and initial length, thrust specific fuel consumption increased slightly as it is shortened.

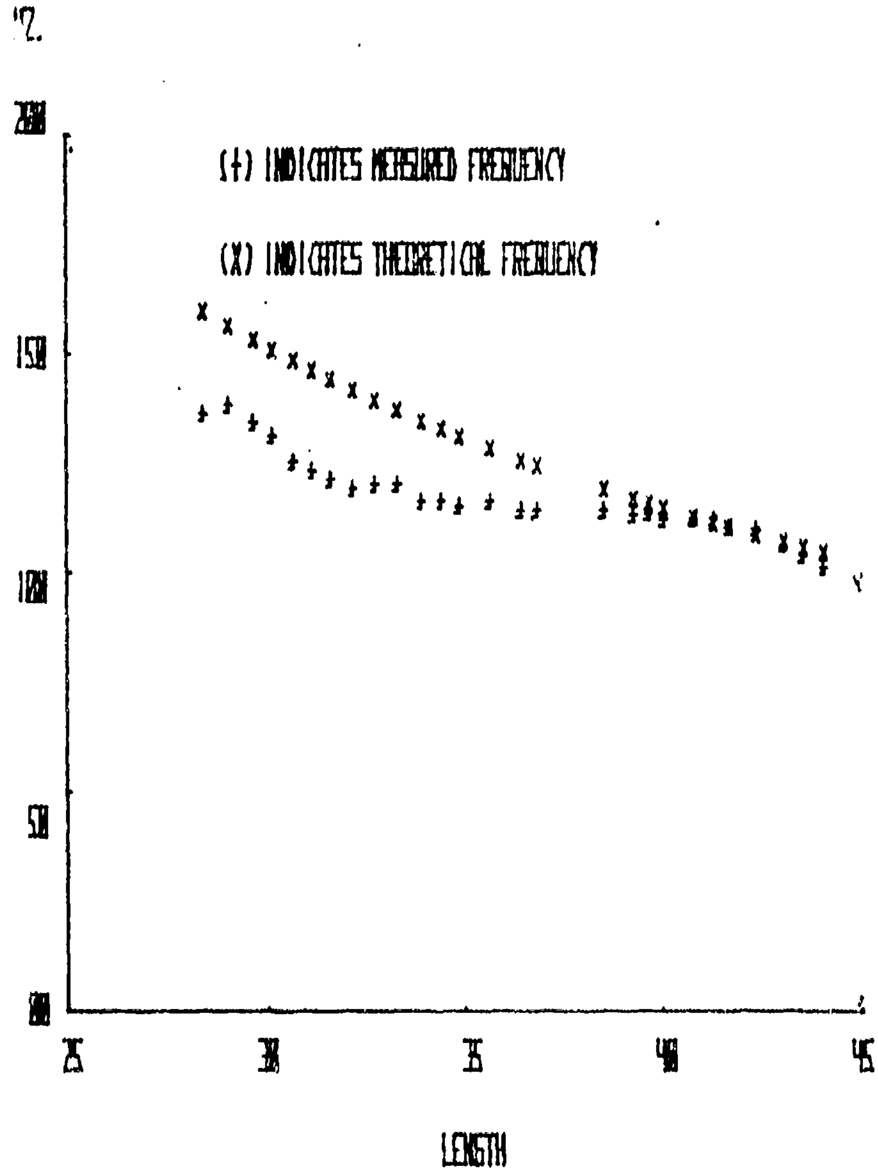

Figure 9 - FREQUENCY VS LENGTH OF PULSEJET

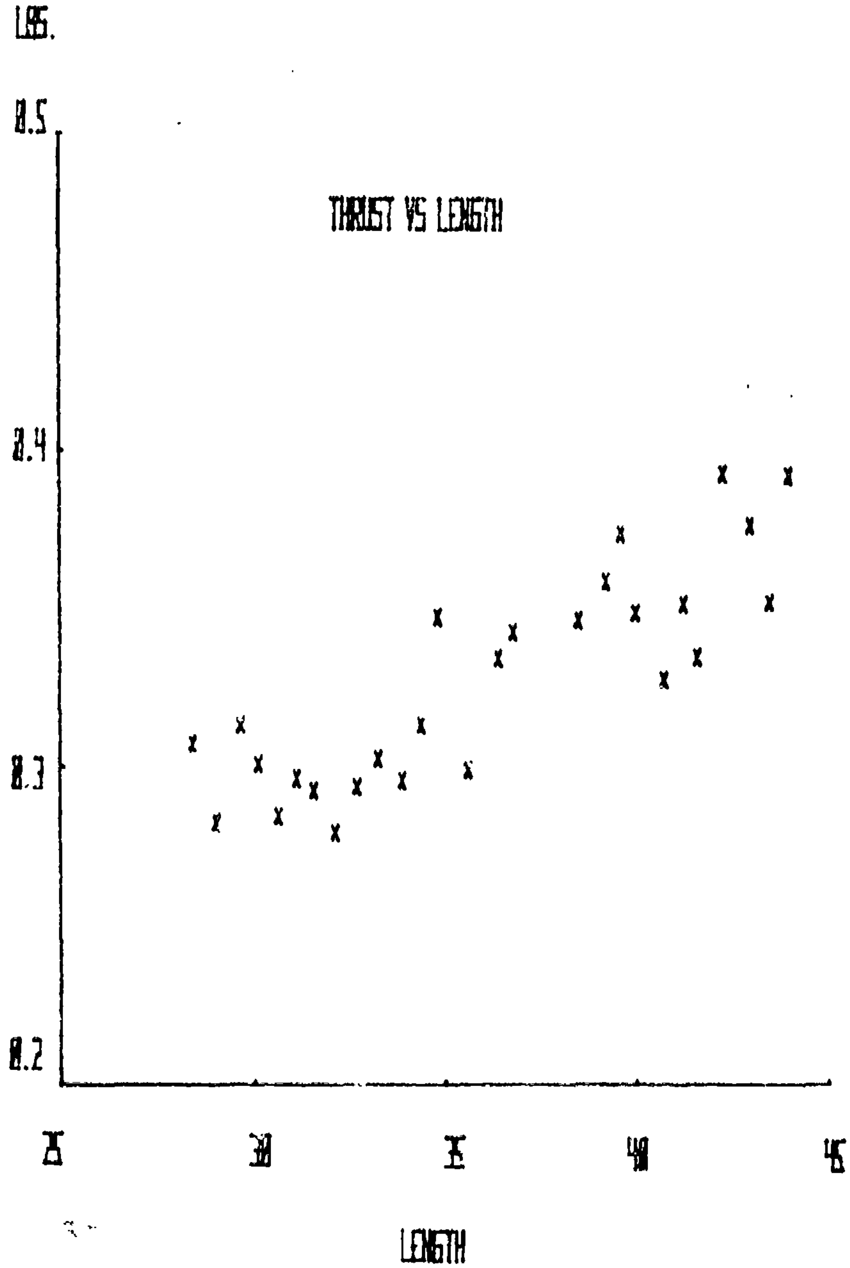

Figure 10 - THRUST VS LENGTH OF PULSEJET

As the pulsejet was shortened below 33 inches, starting became an increasing problem. The needle valve setting controlling the fuel flow became critical with a narrowing limit of starting capability. The final limit of stability was determined by starting capability rather than erratic operation.

Temperature measurements showed that the pulsejet could produce high temperatures(1100 degree F), very close to the exhaust nozzle. These exhaust temperatures increased as the tail pipe was shortened. The pulsating nature and high velocity of the exhaust produced rapid mixing and therefore, rapid cooling of exhaust gases. Combustion chamber temperatures were sufficient to produce a red glow in this portion of the pulsejet. On the first run of this portion of the study, the inlet for the insecticide was left open in error. When the inlet (located approximately 12 inches from exhaust) was plugged, a marked increase of 0.06 pound thrust was noted. This error tended to suggest one method of modulating pulsejet thrust. The pulsejet tested had an estimated mean flow velocity of 300 feet per second and an estimated mass flow rate of $0.1X10^{-3}$ slugs/second. This compares with the 200 feet per second estimate of the pulse reactor mentioned in Lockwood's [13] "Summary Report on Investigation of Miniature Valveless Pulsejets."

Lockwood [13] tested a similar sized device with a maximum combustor diameter of 1.39 inches and an overall length of 25.25 inches with a tapered tailpipe. Thrust and fuel flow measurements were not obtained by Lockwood due to inconsistent operation. The 25.25 inch length was near the limit obtained for the pulsejet used in this thesis.

A number of weaknesses were noted in this method of

study. The hysteresis of the thrust bed was previously mentioned. Experimental scatter cast serious doubt on the validity of fuel measurements, making that portion of the data qualitative at best. An initially longer pulsejet would have helped determine the upper limit for length as opposed to starting somewhere in the middle and working down. Finally, a number of different diameters of pulsejets were needed , though not available to determine the diameter effect on miniaturization.

V. SUMMARY AND CONCLUSIONS

A. PRESENT RESEARCH

Little present research has been directed toward developing pulsating combustion devices in the United States. The Curtis Company is apparently the only large scale pulsejet manufacturing firm in North America. Engineering effort of the Curtis Company has been directed toward improving mechanical valves and finding new applications for existing pulsejets.

Pulsating devices have not gone unnoticed even though significant breakthroughs have not materialized. Germany, Poland, and France have continued to maintain some research effort in combustion oscillation devices.

However, a great deal of research effort has been directed toward suppression of combustion oscillations. While oscillations have remained a nuisance for oil fired boilers, newer and increased power rockets have found a need for a reevaluation of theories of pulsating combustion to determine the mechanisms involved. The future of pulsating combustion applications may rest entirely with spinoffs of the research designed to understand and eliminate it. The full potential of all pulsating devices have yet to be realized.

B. REYNST COMBUSTOR

The Reynst pot has been one of the least explored of pulsating devices. A combustor capable of producing heat and an air flow, with no moving parts, while burning almost any fuel would seem like a device that would be very much in demand, but such is not the case with the Reynst combustor.

The noise produced by the Reynst Pot, while not as great as the pulsejet, is generally offensive unless strongly muffled. With increasing emphasis on noise pollution suppression, noise generation will remain a constraint on its development. Heat is both a benefit and a curse of the combustor. Unless the heat is continuously removed from the pulsating device, oscillations will cease.

Some applications of the Helmholtz resonator (a similar device) have been made in European home heating units. Reynst pot water heaters and boilers have experienced some development, though widespread use remains nonexistent. The forte of this device would be in specialized applications requiring small-sized heating apparatus for pre-heating liquids.

The Reynst combustor has many attributes. Propane, gasoline, methane, kerosene, alcohol and coal dust are just a few of the fuels capable of powering a Reynst combustor. Energy requirements and decreasing petroleum reserves make this "universal fuel" device worthy of greater consideration. The simplicity of the combustor (in final analysis, a closed can with a hole in it), lends itself easily to low cost and mass production, as well as the possibility of near 100% reliability. A final capability of

high combustion intensity per unit volume as compared with other combustion devices opens up many possibilities for combustor applications.

C. PULSEJET

The pulsejet, the most popular pulsating device, has problems similar to the Reynst Pot. One Curtis Company representative speculated that greater use of pulse jets was limited because of their noise. Since the acoustic mechanism is an integral part of the cycle, it would appear that little can be done to eliminate this particular problem. Another problem which must be considered is the high temperature of the combustion chamber and tail pipe. Thinner and lighter metals require cooling of some sort to maintain strength.

It is interesting that most of the modern applications of pulsejets have capitalized on the problems of the device. The high exhaust temperatures and flow velocity have been used to clear runways and railing switches of ice and snow. The military investigated the use of the pulsejet for tunnel clearance in Vietnam. Foggers are another specific application of pulsejets. The Dyna-Jet is an example of a propulsive device for model airplanes that combines speed and small size at low cost. The application of the pulsejet to boundary layer control seems to depend on development of smaller valveless pulsejets.

Other applications that would seem logical are those employing the noise capability of the device. A supportive structure with appropriate diaphragms could use a pulsejet as a driver for a low cost, low frequency acoustic source buoy. The pulsejet could also serve as a propulsive device

for small, low speed drones.

Fuel type requirements are not stringent. A wide variety has been used; however, gasoline seems to be the most commonly used. The high thrust-to-wweight ratio at low cost is a capability that makes the pulsejet an attractive combustion device.

VI. FUTURE RESEARCH

Research is sorely lacking in several areas of pulsejet development. The most pronounced area is that of valve technology. The aerodynamic valve is not understood. Past designs for aerodynamic valves exhibited increased performance at the expense of design simplicity, such as the improvement of the vortex diode over the telsa diode. Theory is so lacking that successful fluidic valve designs are patented and carefully guarded because of their commercial value. Fluidic logic research and frequency response analysis should provide the necessary information for fluidic valve advancement.

Fuel inlets are a major obstacle in the miniaturization of pulsejets. As in the case of valve technology, fuel inlet design and placement are more experimentally determined than theoretically. The pulsejet requires fuel to be added to a device with a rapidly changing pressure gradient while maintaining the simplicity and low cost. Increased effort in this area is essential for miniaturized applications.

The detonation pulsejet is an unusual device of mostly theoretical nature so far. A few laboratory models have been constructed and investigated. In every case, the detonation pulsejet was a one-shot cycle requiring spark ignition to initiate each cycle. The device mentioned by Wojcicki [14] was powered by hydrogen and air, whereas the device of Otgoff [15] worked better with more exotic fuels of ether and acetylene. The great advantages of the detonation pulsejet lie in the low fuel consumption and

supersonic outflow of combustion products. This device has the capability of producing the lowest fuel consumption of all jet engines. In spite of these advantages, the detonation pulsejet has been largely ignored and, therefore, has not begun to achieve its potential. This should be the primary direction of future research.

Research on the Reynst pot has been minimal since the death of Reynst. As a result of this lack of research and application of current technology, the Reynst Combustor has not fulfilled its potential. High conductive liquid filled cooling fins and optimized design of cooling fins could significantly increase the heat transfer and therefore decrease the requirement for water cooling. The use of extremely thin metals with the resulting temperature differential between the fin and the heat sink (whether atmosphere or water), and other developments in heat transfer, should be incorporated in the Reynst Pot.

There have been two methods of fuel introduction for the Reynst Pot in the past, by liquid introduction to a pool in the bottom or by atomized introduction at the mouth. No work has been recorded of variation of fuel introduction such as pressurized fuel injection or positioning of fuel inlets to support the natural cycles of the combustor. Future research in this area would be the second most valuable to the Reynst Combustor.

The most valuable direction of future work on this device would be toward theoretical understanding of the Reynst Pot cycle. While Porter described the blow down portion of the cycle, little has been accomplished toward defining the entire nonlinear cycle. The Lyapunov function and limit cycle modeling are modern control analysis techniques that have the potential to fill some of the theoretical gaps of the phenomenon.

A somewhat distant relative of combustion oscillation is the flame whirl. The vortex that occurs with this form of combustion instability is little understood but has great potential as an energy conversion mechanism.

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